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MAGNETICS/TRANSPORT ASPECTS OF EBTR REACTORS*

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Summary

The magnetics model developed for the ELMO Bumpy Torus Reactor (EBTR) study is described. A multiple-loop current simulation of toroidal-field (TF) and aspect-ratio-enhancement (ARE) coils is used to calculate the vacuum magnetic field. The bounce-averaged vertical drift velocity, v_y, and poloidal drift frequency, Ω, are determined from the field topology. Upon performing the appropriate averages of v_y and Ω, the point-plasma toroidal curvature, R_T, and magnetic curvature, R_c, are obtained for use in modeling EBT transport. In addition, the fraction, f_α, of alpha particles completing their first orbit within the plasma is calculated.

The magnetics code was used to obtain an EBT reactor design with a magnetic aspect ratio, R_T/R_c, of 20 using ARE coils with current, I_{ARE}, equal to -0.22 of the TF coil's current, I_{TF}. A 36-coil torus results with a major radius, R, of 35 m, an average minor radius, r_p, of 1 m, a mirror ratio, M, of 2.24, an average toroidal field, B, of 3.64 T, and a peak field at the TF coil, B_c, of 9.7 T. Sensitivity studies about the design point indicate that R_T/R_c is most sensitive to variations in N, R, and I_{ARE}/I_{TF}.

Introduction

One of the major goals of the EBTR magnetics study[1] is to quantify by means of a simplified but self-consistent model the effectiveness of realistic coil arrangements in providing aspect-ratio enhancement (ARE) of the bumpy-torus configuration. The approach followed here for the reactor is a modification of that used in previous studies[2,3] to produce relevant transport coefficients at low beta. The procedure, briefly stated, is to calculate v_y and Ω from the vacuum field and then form the diffusion coefficient, $D_{nv} = \nu(v_y/\omega)$, from which the confinement time, $\tau_p = 1/D_{nj}$, can be obtained. These models are based upon an infinite-bumpy-cylinder representation of the vacuum magnetic field. The infinite-bumpy-cylinder model, however, does not contain sufficient information with which to assess accurately the effectiveness of ARE coils. Those reactor magnetics studies which realistically simulate the magnetic field have evaluated various coil configurations on the basis of particle confinement in vacuum magnetic fields[4,5] rather than upon transport coefficients. Consequently, a magnetics/transport model described below was developed, which uses the results from the magnetics calculations to perform averages of transport-related parameters for use in a point-plasma model.[1]

Magnetics/Transport Model

Magnetic Field

One simplification of the magnetic field problem is to consider only the vacuum magnetic field. The calculation of the vacuum field, as well as estimates of parameters that depend on the magnetic field, can be simplified even further by assuming that sufficient knowledge of poloidal asymmetries is retained when limiting all calculations to the equatorial plane.

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The vacuum magnetic field is obtained by simulating the TF and ARE coils by combinations of filamental loop currents. Formulae are readily available[6] for calculating the magnetic field components resulting from a single filamental loop current. The vacuum magnetic field is subsequently obtained by summing the field components from each filamental loop current.

The TF coils are simulated with a 4 x 8 matrix of loop currents as shown in Fig. 1. The eight loop currents composing each row of the matrix are of equal radius and are distributed uniformly along the toroidal length of the coil. The four rows are also distributed uniformly in the radial direction. The camber of each current loop is chosen to ensure that the plane containing a current loop is parallel to the coil plane.

Each ARE coil is simulated with a circular cross section containing four loop currents (Fig. 1). All loop currents lie on a circle dividing the cross-sectional area in half and are equidistant from each other. The loops are positioned on the circle such that each pair of loops are of equal radius. The current, I_{ARE}, in an ARE coil is expressed as a variable fraction of the total current, I_{TF}, in a TF coil. The selection of the ARE-coil camber represents a compromise between a desire to maximize its effect and engineering practicalities. The optimal location of the ARE coils with respect to both transport and orbit confinement is in the midplane with the ARE coil center located approximately at the outboard plasma surface. However, neither transport nor orbit confinement is very sensitive to the ARE coil location as long as its center is near the outboard plasma surface. Consequently, the EBTR maintanence scheme suggested the ARE-coil location shown in Fig. 1. Other aspect-ratio-enhancement techniques, such as symmetrizing coils,[4,5] have not been considered in this study.

Drift Velocities

In addition to the detailed magnet design parameters, two transport parameters are derived from the magnetics model previously described: the toroidal radius of curvature, R_T, and the magnetic radius of curvature, R_c. Both R_T and R_c determine the average vertical drift velocity, v_y, and the gradient-B drift frequency, Ω, respectively. By using a bounce-averged formalism[7,8] for the calculation of the particle drift velocities, the toroidal dimension is eliminated from the problem.

The gradient-B drift frequency, Ω, can be derived from the second or longitudinal invariant, $J = m\oint d\ell\, v_\parallel$, where the integration of $v_\parallel$ is performed over a complete traverse of a particle trajectory along a field line. The prescription for calculating the bounce-averaged poloidal drift frequency from J is given by[7]

$$\Omega = \frac{1}{mr\omega_c\tau}\frac{\partial J}{\partial r} \quad . \tag{1}$$

The bounce period, τ, is defined by $\tau = \oint d\ell/v_\parallel$, ω_c is the cyclotron frequency, and r is the radial location of the field line measured relative to the center of the particle orbit (i.e., the radial location where

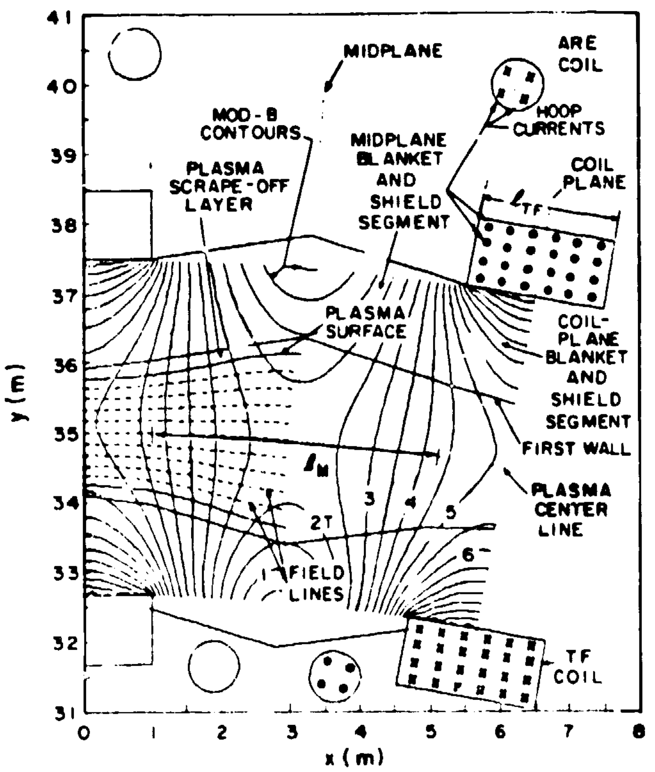

Fig. 1. The first-wall/blanket/shield geometry adopted for the EBTR design study.

$\partial J/\partial r = 0$). The above line integrations need only be performed over that portion of a particle trajectory located between the midplane and the relevant mirroring point. In the case of a passing particle (i.e., a particle with a parallel velocity, $v_\parallel$, that is sufficient to preclude reflection by the mirror field), the mirroring point is replaced by the location of the particle trajectory in the coil plane.

The parallel velocity is calculated by invoking conservation of both kinetic energy and magnetic moment along a field line, but neglecting the energy stored in the electric field. Kinetic energy and magnetic moment continue to be conserved as a particle drifts poloidally from one field line to another. Then,

$$v_\parallel = v_M \left[1 - \sin^2\zeta(r_M) \frac{B(r,\ell)}{B(r_M,0)}\right]^{1/2} \quad , \tag{2}$$

where v_M is the particle speed in the midplane, $\zeta(r_M)$ is the pitch angle at the midplane radius, r_M, and $B(r_M,0)$ and $B(r,\ell)$ are the magnetic field evaluated in the midplane at r_M and at a distance, ℓ, along the field line passing through the midplane at r.

The average vertical drift velocity is obtained by performing a bounce average of the local vertical drift velocity, v_D.[4] That is

$$v_y = \tau^{-1} \oint d\ell \; v_D/v_\parallel \quad , \tag{3}$$

where

$$v_D = \frac{m v_M^2}{2qB(r,\ell)R(\ell)} \left[2 - \sin^2\zeta(r_M) \frac{B(r,\ell)}{B(r_M,0)}\right] \quad . \tag{4}$$

Point-Plasma Transport Parameters

The definitions of the average vertical-drift velocity and poloidal-drift frequency used by the point-plasma model of Ref. 1 are given by, respectively, $v_y \equiv k_B T_j/q_j B R_T$ and $\Omega \equiv k_B T_j/r_p q_j R_c B$, where T_j and q_j are the temperature and charge of the jth species and k_B is the Boltzmann constant. These definitions provide no insight into the details of the averaging process necessary to generate zero-dimensional parameters for use in a point-plasma model. An examination of the derivation of the plasma diffusion coefficient, D_{nj}, and the particle confinement time, τ_{pj},[2,3] suggests the following scheme for calculating R_T and R_c; Eq. (5) is to be used when a ratio of R_T and R_c is needed and Eqs. (6) and (7) when needed individually.

$$\frac{R_T}{R_c} = \langle (r\Omega/v_y)^2 \rangle^{1/2} \quad , \tag{5}$$

$$R_T = \frac{k_B T_j}{q_j B \langle v_y \rangle} \quad , \tag{6}$$

and

$$R_c = \frac{k_B T_j}{q_j B \langle r\Omega \rangle} \quad , \tag{7}$$

where $\langle\rangle$ denotes an average over a Maxwellian distribution of temperture T_j. The radial variation of the drift velocities is treated by computing Eqs. (5), (6), and (7) at the plasma edge, because plasma diffusion is primarily an edge effect. Any asymmetry in the radial profiles is taken into account by using the arithmatic mean of the inboard and outboard edge values.

First-Orbit Losses

The largest orbit contained within the reactor vessel defines that region of the plasma in which no first-orbit losses occur. This last closed orbit is used to calculate the fraction, f_α, of alpha particles that survive a first-orbit trajectory. Such an orbit or drift surface is defined as a surface comprised of field lines of constant J. For monoenergetic alpha particles a drift surface depends only on magnetic moment or $\cos\zeta(r_M)$. Assuming circular orbits, the cross-sectional area of the last closed drift surface is calculated as a function of pitch angle. Assuming both a parabolic density profile and a flat temperature profile, the fraction of alpha particles that survive first-orbit losses is given by

$$f_\alpha = \frac{\int_0^{r_p} f_c(r)\, n^2(r)\, r dr}{\int_0^{r_p} n^2(r)\, r dr} \quad , \tag{8}$$

where $f_c(r)$ is the fraction of the local isotropic pitch-angle population residing on contained orbits that pass through the radius r.

Magnetics/Transport Results

Effects of ARE Coils

The ARE coils improve EBT transport properties through changes in $R_c \sim B/(dB/dr)$ by modifying the magnetic field so that the field profiles resemble those found in configurations with larger aspect ratio and, hence, better transport properties. The magnitude of the change in the ratio R_T/R_c that can be produced is shown in Fig. 2. The modification of the field profiles is obtained at the expense of increased field, B_C, at the TF-coil and an increased mirror ratio, M, as is demonstrated by a traverse along a line of constant N in Fig. 2. An increase in R_T/R_c can also be obtained by changing N (or M) for fixed I_{ARE}/I_{TF}, but not with the economy in B_C that results when I_{ARE}/I_{TF} is changed. The current ratio, I_{ARE}/I_{TF}, cannot be increased without limit, however, because the

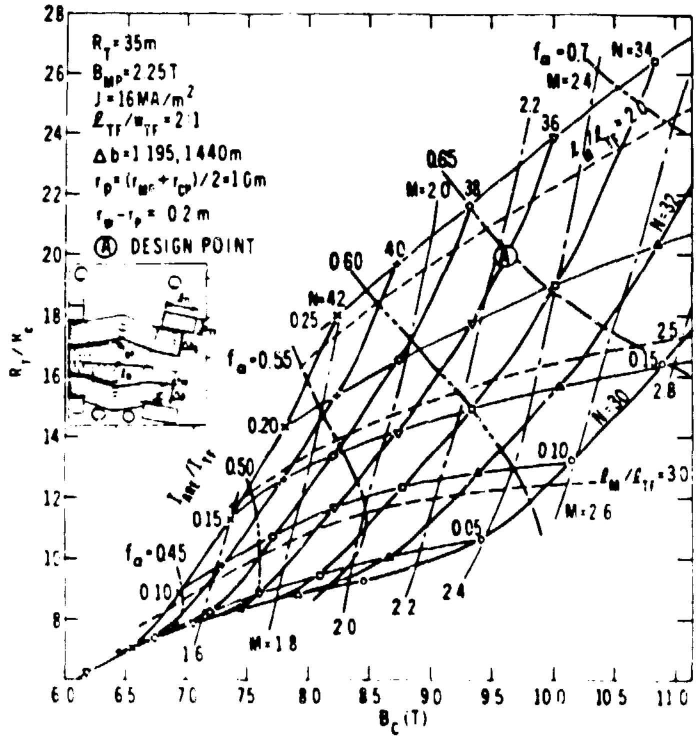

Fig. 2. The influence of ARE coils on plasma transport and alpha-particle confinement.

capability, as measured by ℓ_M/ℓ_{TF}, worsen with increasing I_{ARE}/I_{TF}. A value of ℓ_M/ℓ_{TF} equal to two was taken as a lower limit on the basis of a tritium breeding constraint,[1] thereby defining the lowest degree of accessibility acceptable to the EBT reactor design. A second benefit of increasing I_{ARE}/I_{TF} is an increase in f_α (Fig. 2). This result is a by-product of the field profile modification by ARE coils in that changes in the field profiles tend to align the particle orbit centers over the entire spectrum of pitch angle space. The f_α results of Fig. 2 are lower than those obtained for typical experimental parameters, where f_α = 0.93. This difference in f_α between the experimental regime and the reactor regime is graphically demonstrated in Fig. 3. The decrease in f_α for typical reactor parameters relative to typical experimental parameters is the result of inserting a blanket/shield and pumped limiter between the plasma and the TF coils. The difference between the typical reactor parameters (R = 60 m, I_{ARE}/I_{TF} = 0, f_α = 0.64) and the design point parameters (R = 35 m, I_{ARE}/I_{TF} = -0.22, f_α = 0.65) is negligible with respect to the total population of confined alpha particles. However, the use of ARE coils permits the attainment of the same f_α in a much smaller device (R = 60 m versus R = 35 m) and an increased passing particle population albeit at the expense of the trapped particle population. The inaccuracy in the f_α results introduced by considering only the equitorial plane (and thereby neglecting the contribution from non-circular orbits) is $\lesssim$ 10%.

Magnetics Design-Point

The magnetics design selected for the EBTR design point had to satisfy several criteria,[1] which are summarized in Table 1. Figure 2 depicts a typical set of magnetics design curves. These data meet a priori as many of the design criteria of Table 1 as possible. The point A shown in Fig. 2 was chosen as the magnetics design point for its compliance with the remainder of

TABLE I
DESIGN POINT CRITERIA

Parameter	Value
Current density, J (MA/m²)	16
Ratio of TF-coil toroidal length to radial width, $\ell_{TF}:w_{TF}$	2:1
Scrape-off thickness under TF coil, $r_w - r_p$ (m)	0.20
Blanket thicknesses, Δb (m)	
• Inboard thickness	1.195
• Outboard thickness	1.440
Plasma major radius, R_T (m)	35
Average plasma radius, r_p (m)	1.0
Midplane magnetic field, B_{MP} (T)	2.25
Transport parameter, R_T/R_c	20
Mirror ratio, M	~ 2
Accessibility to torus, ℓ_M/ℓ_{TF}	$\geq$ 2
Peak field at TF coil, B_C(T)	$\lesssim$ 10

TABLE II
SUMMARY OF RESULTS FROM EBTR MAGNETICS DESIGN
(POINT A ON FIG. 2)

Parameter	Value
Plasma center, R(m)	35.00
Plasma radii (m)	
• Midplane, r_{MP}	1.24
• Coil plane, r_{CP}	0.76
• Average, $r_p \equiv (r_{MP} + r_{CP})/2$	1.00
Magnetic field (T)	
• Midplane, B_{MP}	2.25
• Coil plane, B_{CP}	5.03
• Average, $B \equiv (B_{MP} + B_{CP})/2$	3.64
• Peak field at TF coil, B_C	9.63
Current per TF coil, I_{TF} (MA)	31.35
Current per ARE coil, I_{ARE} (MA)	6.97
Coil dimensions (m)	
• TF-coil length, ℓ_{TF}	1.98
• TF-coil width, w_{TF}	0.99
• Radius of current center, r_c	2.90
• Radius of TF coil center, R_{TF}	35.08
• ARE-coil radius, r_{ARE}	4.44
• ARE-coil diameter, d_{ARE}	0.74
Number of bumps, N	36
Mirror ratio, $M \equiv B_{CP}/B_{MP}$	2.24
Magnetic aspect ratio, R_T/R_c	20.98, 19.02[a]
Toroidal radius of curvature, R_T (m)	37.48, 40.03[a]
Magnetic radius of curvature, R_c (m)	1.30, 1.40[a]
Alpha-particle trapping fraction, f_α	0.65
Accessibility to torus, ℓ_M/ℓ_{TF}	2.09

[a] The two values given per entry represent values taken at the inboard and outboard plasma edges in the equatorial plane. An arithmatic mean of the two values is used in the point-plasma model.

the design criteria, as is seen from Table 2. The physical layout of the magnets, plasma, and blanket/shield associated with this magnetics design point is shown in Fig. 1. The remaining relevant parameters pertaining to the magnetics design point are also included in Table 2.

Sensitivity studies about the design point indicate R_T/R_c and f_α are most sensitive to changes in N, R, and I_{ARE}/I_{TF} and least sensitive to changes in r_p and B. Although increasing either R or $|I_{ARE}/I_{TF}|$ or decreasing N yield improved values of R_T/R_c and f_α, only small deviations from the design point values can be tolerated before violating one of the last three design criteria of Table 1. Either the examination of other aspect-ratio-enhancement schemes or a relaxation

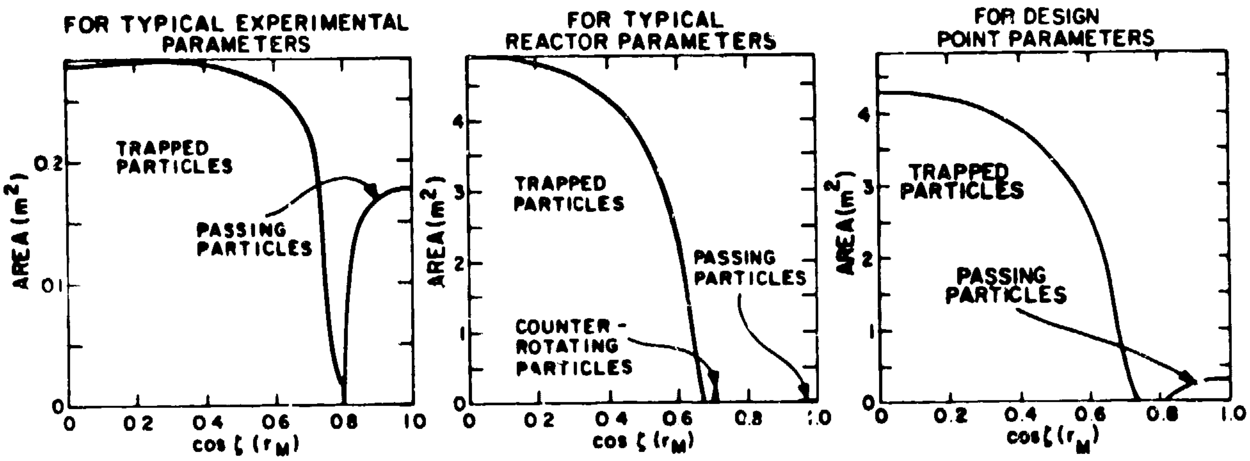

Fig. 3. The cross-sectional area of the largest drift surface contained within the vacuum vessel versus cos ζ(r_M) for typical experimental parameters, typical reactor parameters, and the design point parameters. The ordinate ranges from 0 to the cross-sectional area of the vacuum vessel.

in the design criteria is needed to provide improvement in the magnetics performance of this design.

Conclusions

The use of ARE coils can result in the enhancement of the transport parameter, R_T/R_c, by a factor of 2 or more for the design range investigated while meeting engineering constraints imposed by magnet technology, reactor accessibility, etc. The use of ARE coils, therefore, permitted the design of an EBT reactor that can be as small as 35-m in major radius and 1-m in minor radius. In addition, R_T/R_c was found to be most sensitive to variations in N, R, and I_{ARE}/I_{TF}. Decreasing N is the most practical method of enhancing R_T/R_c provided the mirror ratio constraint can be increased.

The ability to retain 3.5 MeV alpha particles, as measured by f_α, is a source of concern. However, not all of the factors which affect particle orbits (and also transport) have been included in these calculations. The effects due to the presence of the electron rings, a finite-beta plasma, and the ambipolar electric field have been neglected here and need to be included in subsequent analyses as they may ameliorate this problem.

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